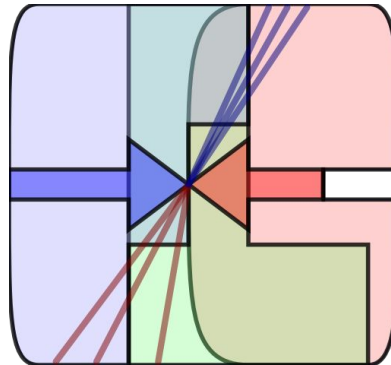


Status of e^+e^- spin/mixture studies

Snowmass Energy Frontier
Workshop, BNL
April 5, 2013
J.List (DESY)



Particles, Strings,
and the Early Universe
Collaborative Research Center SFB 676



The Charge

- Especially in the case of e^+e^- , we wanted to see where the prior studies stand.
 - 1. what has been studied
 - 2. what are the techniques used to measure spin/mixture
 - 3. what to expect for exotic non-zero spin measurements / exclusion
 - 4. what to expect for the measurement / exclusion of CP-violating contribution in bosonic couplings
 - 5. what to expect for the measurement / exclusion of CP-violating contribution in fermionic couplings

Disclaimer

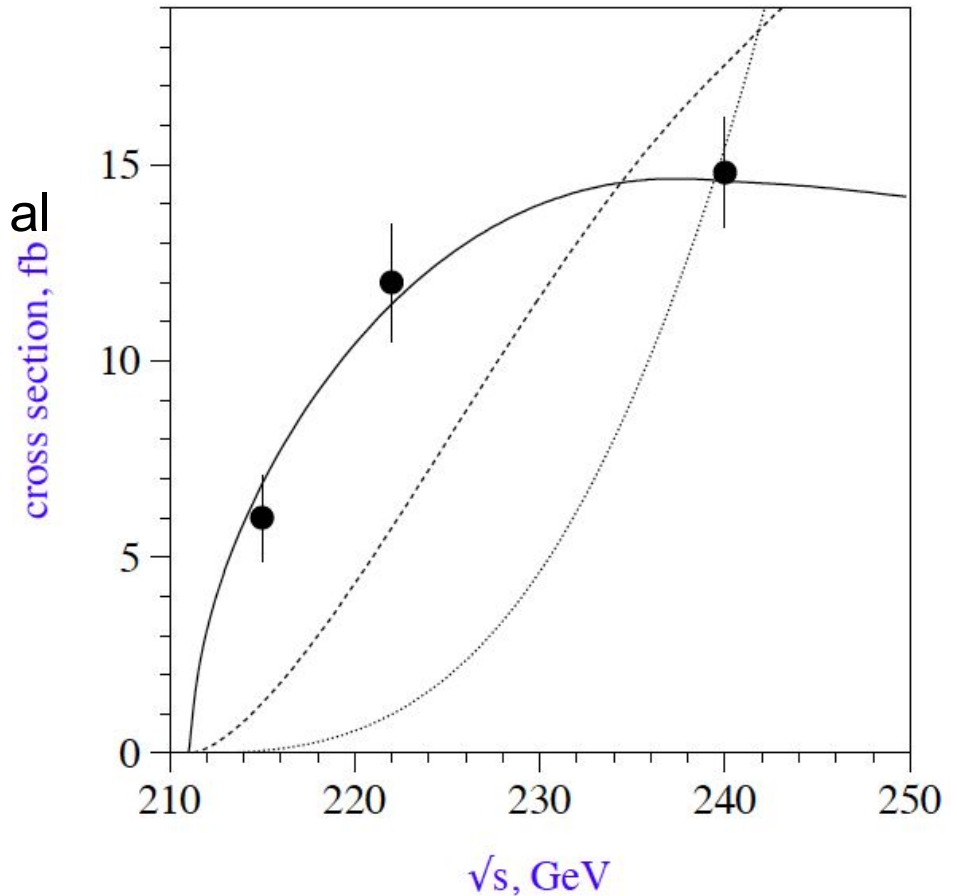
- None of the work presented here has been done by me
(but at least in the group I was in at the time....)
- I'll do my best to summarize the status
- Emphasis on detector level studies – that's what we trust in more....
- Apologies if I missed something – I'm happy to hear about any additional studies, please come forward!

Detector Level Studies

- Spin-Parity from threshold scan
- CP even/odd mixing in hZZ coupling (ie. bosonic)
 - Scalar/pseudoscalar mixing in decays to tau-leptons (ie. fermionic)

The Textbook Plot

- J^P determination from shape of threshold
- Status: from TESLA TDR, cf. LC-PHSM-2001-055, Lohmann et al
- $M_H = 120$ GeV
- 20 fb^{-1} / point
- Discrimination of $J^P = 0^+, 1^-, 2^+$ on 10^{-5} level
- Would we learn something important from an update?



CP Mixtures in Bosonic Couplings

- In addition to CP-even, SM-like s-wave amplitude \mathcal{M}_{HZ} , allow CP-odd p-wave amplitude \mathcal{M}_{AZ} with coupling η :
$$\mathcal{M}_{\phi Z} = \mathcal{M}_{\text{HZ}} + \eta \mathcal{M}_{\text{AZ}} \quad , \eta \text{ purely virtual, SM: } \eta = 0$$
- MSSM: ZZA vertex forbidden at Born-level, η loop-induced
2HDM or other Higgs extensions:
 η could be arbitrarily large!
- Effects of η : absolute square of matrix element contain
 - CP violating term $\sim \eta \rightarrow$ forward-backward asymmetry
 - CP conserving term $\sim \eta^2$
 - \rightarrow increase in total x-section
 - \rightarrow but sign ambiguity!

Accessing the CP-violating term

- 3 possibilities:
 - $\cos\theta$ distribution
 - Optimal observable

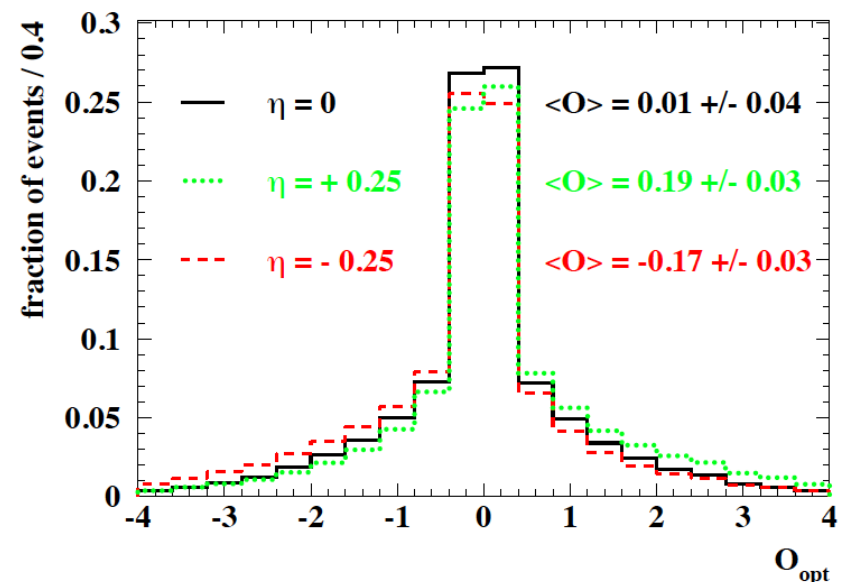
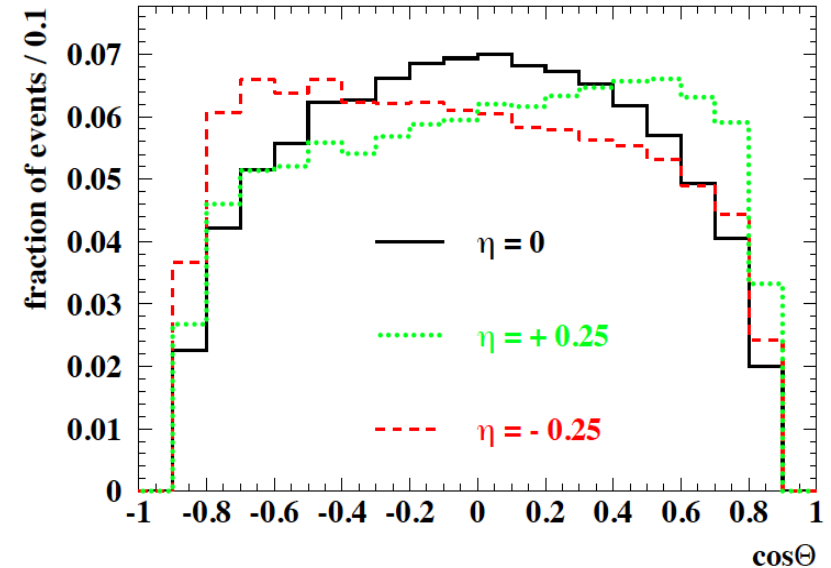
$$O = \sigma_{\text{CP}} / \sigma_{\text{SM}}$$

$$= 2\text{Re}(\mathcal{M}_{\text{ZA}}^* \mathcal{M}_{\text{ZH}}) / |\mathcal{M}_{\text{ZH}}|^2$$

- Mean $\langle O \rangle$

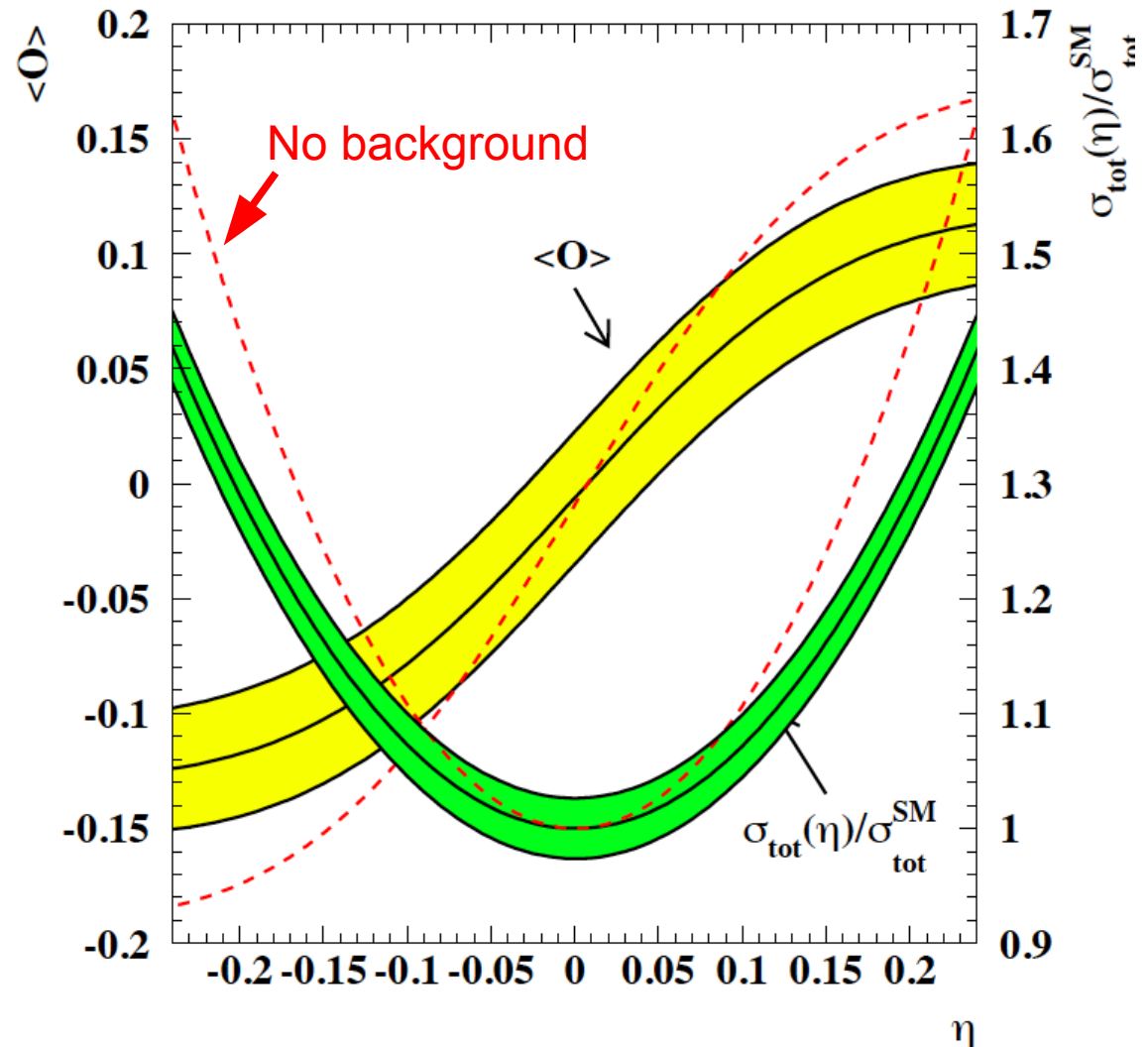
- Which gives best sensitivity?

method	w/o σ_{tot}	with σ_{tot}
	$\Delta\eta$	
$\cos\theta$	0.046	0.033
$\text{opt. obs. } O$	0.032	0.026
$\langle O \rangle$	0.032	0.026

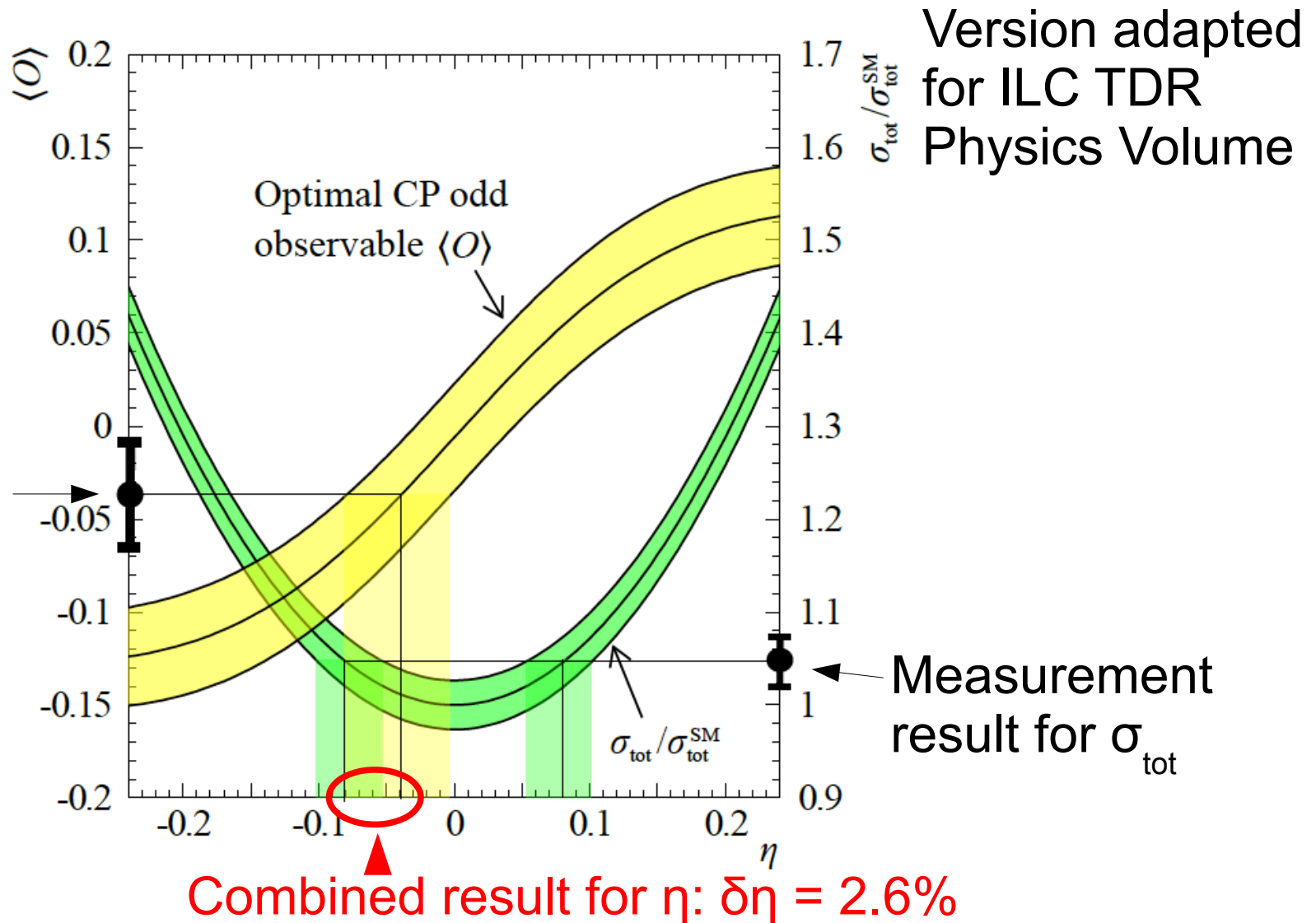


Calibration Curves and Effect of Background

- Optimal observable gives clear gain over $\cos\theta$
- $\langle O \rangle$ as good as full distribution
- Combination with total x-section helps further
- Residual background in final sample
→ changes calibration curves



Summary of Measurement



Comments on Status

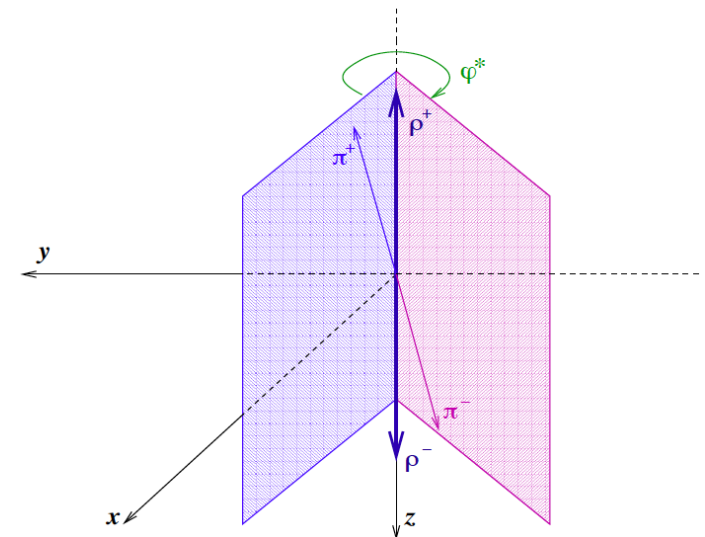
- Study done for $E_{\text{CM}} = 350 \text{ GeV}$, $m_h = 120 \text{ GeV}$, 500 fb^{-1}
 - Based on $ZH \rightarrow \mu\mu H$
 - Should work better at 250 GeV:
 - better momentum resolution
 - Higher cross-section
 - What about electrons?
 - For total cross-section: also $Z \rightarrow \text{hadrons}$?
- => should be interesting to update – any volunteers?*

Scalar / Pseudoscalar Mixing Angle in $h\tau\tau$ Coupling

- ZH/ZA with $H/A \rightarrow \tau^+\tau^- \rightarrow \rho^+\nu\rho^-\nu \rightarrow \pi^+\pi^0\nu\pi^-\pi^0\nu$
- Acoplanarity angle φ^* between ρ decay products in restframe of $\rho^+ \rho^-$ system
- Divide events into two classes:
 $y_1 y_2 > 0$ and $y_1 y_2 < 0$, with

$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}; \quad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}},$$

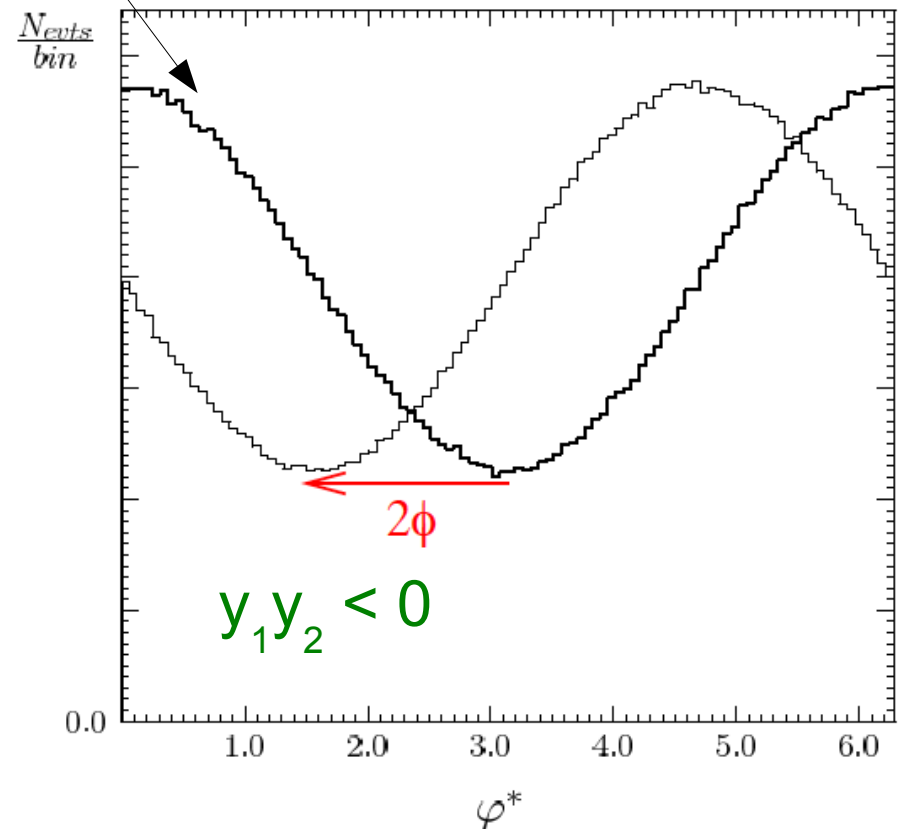
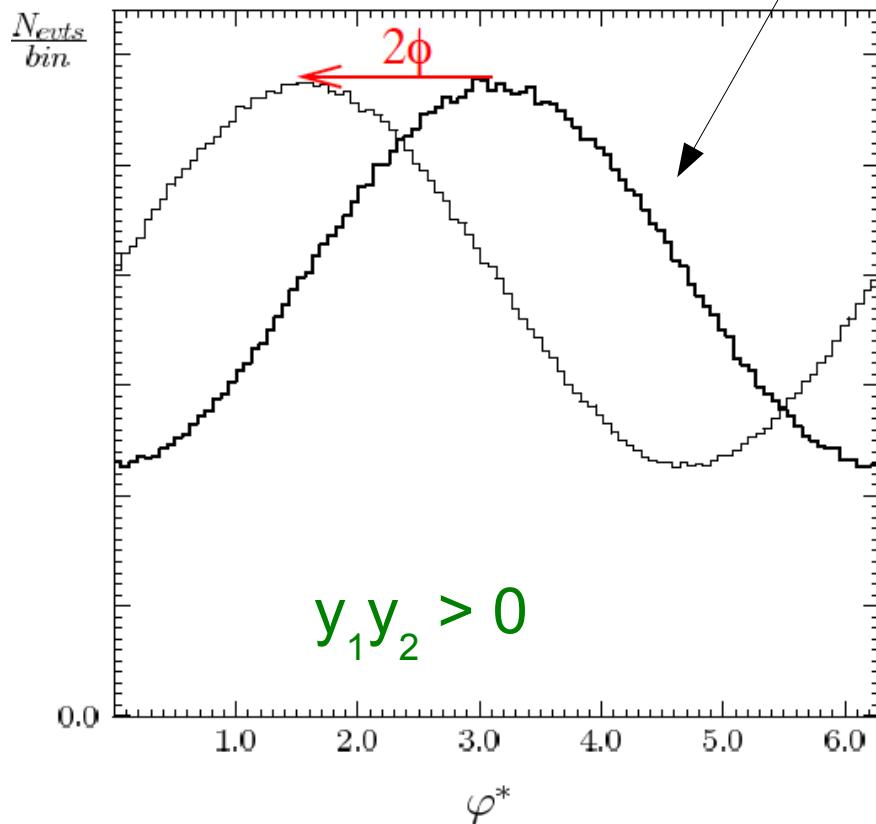
- Expect shift in φ^* distribution ~ 2 mixing angle
- Problem: Neutrinos!



First Step: Cheat τ restframes

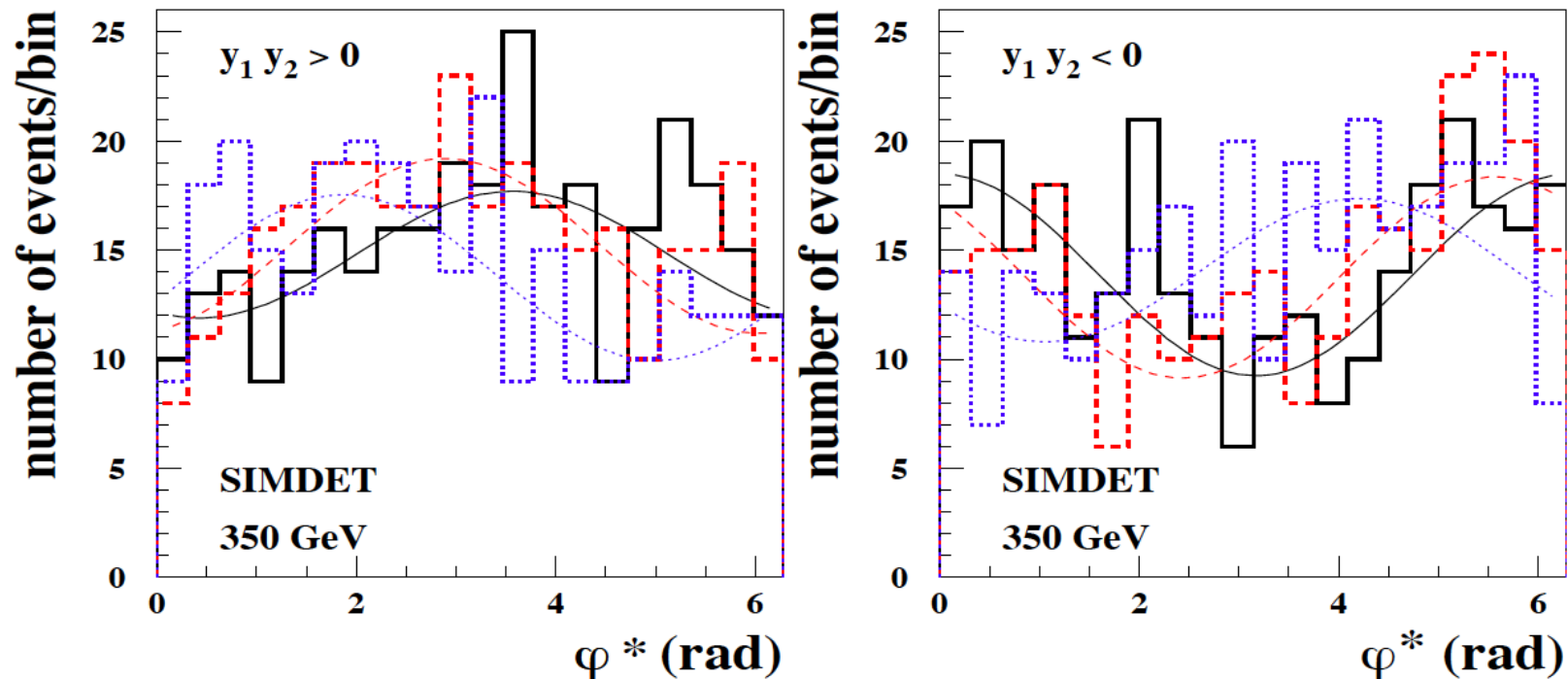
- $E_{\text{CM}} = 350 \text{ GeV}$, $m_h = 120 \text{ GeV}$

Standard Model



Real Life: reconstructed τ restframes

- $E_{\text{CM}} = 350 \text{ GeV}$, $m_h = 120 \text{ GeV}$, 500 fb^{-1} :



=> Can determine mixing angle to $\pm 6^\circ$ (1 ab^{-1})

- Many possible improvements: eg. other decay modes

Theory Studies

More on $h \rightarrow \tau^+ \tau^-$:

- Krämer, Kühn, Stong and Zerwas
- Berge, Bernreuther, Spiesberger

At higher energies: $t\bar{t}H$

- \rightarrow excellent talk by M. Mühlleitner at
LCForum Feb 2012, DESY

<https://indico.desy.de/getFile.py/access?contribId=45&sessionId=3&resId=0&materialId=slides&confId=4980>

Spin and CP determination in ttH

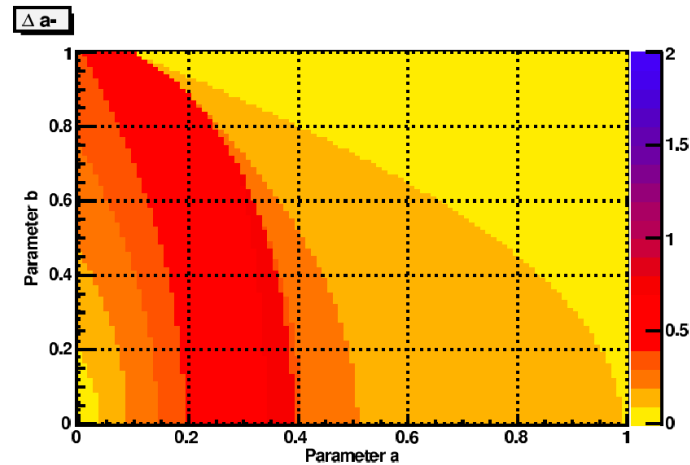
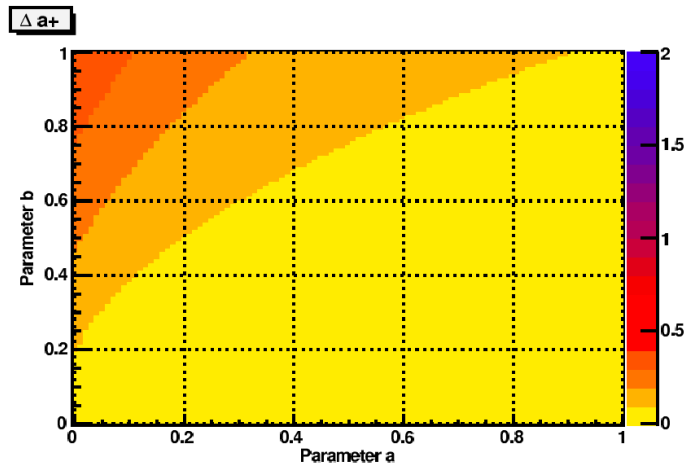
- Coupling of general CP-mixed state Φ to tt:

$$C_{tt\Phi} = -i \frac{e}{\sin \theta_W} \frac{m_t}{2M_W} (a + ib\gamma_5) \equiv -ig_{ttH} (a + ib\gamma_5)$$

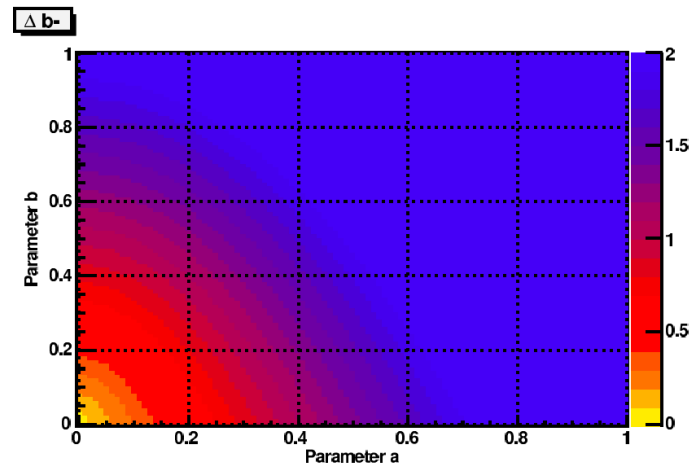
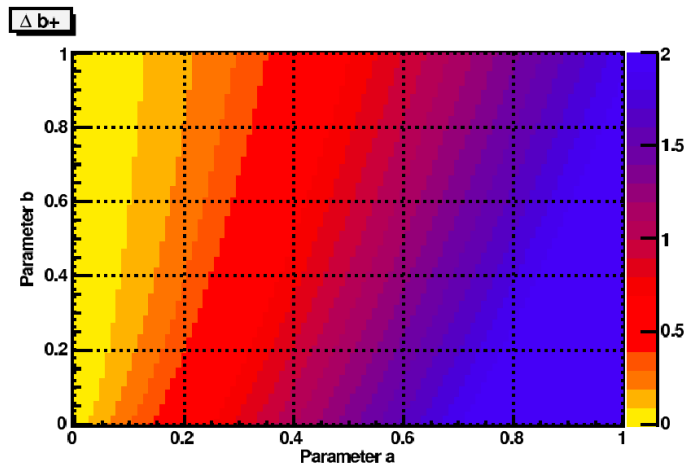
$$a, b \in [-1, \dots, 1]$$

- Observables:
 - Total cross-section and its energy dependence (CP-even!)
 - Top quark polarisation asymmetry
 - Up-down asymmetry of t => can directly probe CP violation

Combined sensitivity on a and b at 800 GeV



Polarisation of
both beams
essential!



Conclusions

- e^+e^- collisions at the ILC allow *model-independent* measurement of CP mixture of Higgs boson
- Bosonic couplings: hZZ , determine admixture to 2-3%
- Fermionic couplings: $h \rightarrow \tau\tau$, tth
- Beam polarisation important
- Detector level studies need updates – volunteers?
- No detector level study for CP study in tth yet – volunteers?